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# BLAST OPERATIONAL OVERPRESSURE MODEL (BOOM): AN AIRBLAST PREDICTION METHOD

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Final Report





AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
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Airblast predictions and measurements are needed for ~~Air Force Weapons Laboratory (AFWL)~~ high-explosive test programs. Airblast predictions using the ~~AFWL/Staff Meteorology Office~~ Blast Operational Overpressure Model (BOOM) are validated with far-field measurements. The BOOM is adapted from a Naval Surface Weapons Center (NSWC) technique. The BOOM incorporates a single function, rather than computer-intensive ray-tracing methods, to account for atmospheric refractive effects on airblast propagation. This makes the BOOM particularly suitable for field work at remote sites where there is no access to mainframe computers. Airblast measurements from conventional weapon detonations validated, with slight modifications, the ~~NSWC~~ technique. Additionally, a method to predict the airblast emanating from beneath a soil overburden has been developed. The method is based upon the mass of overburden covering the explosives. A listing is included of the BOOM computer program written in BASIC programming language to run on a portable microcomputer. Keywords;


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Meteorolcgical phenomena
Overpressure
Predictions
~~Propagation~~
~~Sound transmission~~
Surface burst
Underground explosions
Wave propagation

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# PREFACE

This effort stemmed from the Air Force Weapons Laboratory's (AFWL) concern to conduct high-explosive testing under favorable atmospheric conditions, thus insuring a minimal impact to off-site communities. Many people participated in this effort.

Atmospheric measurements were needed for airblast predictions. Airblast measurements were made to protect the Government from invalid damage claims and to add to the general airblast propagation data base. Dr Robert E. Reinke (AFWL/NTES) modified existing equipment to measure airblast. Mr John A. Leverette (AFWL/NTES) performed the bulk of maintenance, data reduction and operation of the equipment for field testing. For tests at Yuma, Arizona, the U.S. Army Atmospheric Sciences Laboratory at the Yuma Proving Ground made measurements of upper level wind velocity and temperature. For the larger Yuma tests, a weather team from the Yuma Marine Corps Air Station provided us with low-level wind observations at the test site. Finally, Major Jon Kahler's (USAF, Retired, formerly of AFWL/WE) technical guidance throughout this project was especially appreciated.

Metric units are used throughout this report. Exceptions are made for some meteorological parameters which are used in the most commonly reported format as follows: Windspeed in knots, atmospheric pressure in millibars, and the height of the weather data in feet. Conversion factors are as follows: 1 knot = 0.5148 m/s, 1 millibar = $10^2$ pascals, and 1 kft = $10^3$ ft = 304.8 m. All logarithms are to the base ten.

Any reference to specific brand names is made for identification only and does not imply endorsement or criticism by AFWL.

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# INTRODUCTION

The Staff Meteorology Office of the Air Force Weapons Laboratory (AFWL/WE) is tasked to monitor atmospheric conditions and predict far-field airblast propagation for AFWL high-explosive test programs. Under certain weather conditions, unacceptable airblast may propagate to nearby communities and produce minor structural damage or excessive noise irritation. Airblast propagation predictions, based on the state of the local atmosphere and the explosive amounts, are needed for the tests to safely proceed with the assurance of no off-site damage and the minimum of community noise irritation.

These AFWL high-explosive tests involve conventional weapons and chemical detonations with explosive yields ranging from 100 to over 1,000,000 kg. Tests are conducted either locally at Kirtland Air Force Base, New Mexico, or at a remote range near Yuma, Arizona. The airblast prediction technique for these tests must be accurate, incorporate changing weather conditions, and be adaptable for field operations at remote sites. This report describes the AFWL/WE airblast prediction model which meets the criteria, and presents the results of both conventional weapons and chemical high-explosive test series.

## BACKGROUND

For far-field airblast propagation, the atmosphere acts as a lens to refract the airblast wave either upward or back to the ground surface. In the far-field, a shock wave from an explosion moves with the speed of an acoustic wave. Thus, the degree of refraction depends upon the speed of sound in layers of the atmosphere above the ground surface. For the purposes of this report, the use of the term "sound speed" will imply the total sound speed in a particular direction. At any given level, the total sound speed along a specified direction is approximately equal to the temperature dependent sound speed of the air plus the wind velocity component as given by the equation:

$$VS = 331 * [1 + (T/273)]^{1/2} - WS * COS(WD - DI) \qquad (1)$$

where

| | | |
|---|---|---|
| VS = | Total sound speed in the DI direction | (m/s) |
| DI = | Selected direction of interest: Azimuth angle, clockwise from true north (360 deg) as viewed from the explosive source | (deg) |
| T = | Air temperature | (°C) |
| WS = | Wind speed | (m/s) |
| WD = | Azimuthal direction from which wind is blowing; clockwise from true north | (deg) |

A sound speed vertical profile is constructed from temperature and wind velocity measured at selected altitudes. The magnitude of airblast propagation is dependent on the shape of the sound speed vertical profile and the size of the difference between the surface sound speed and the values aloft. If the sound speed decreases with altitude, the blast wave front will be refracted aloft and sound amplitude will be diminished at the surface. Conversely, when the sound speed at some height exceeds the surface value, a portion of the wave front will be refracted back to the surface with an ensuing sound enhancement.

Ray tracing techniques are frequently used to compute atmospheric airblast refraction. Several techniques are available which have been used with success at other locations. Table 1 provides information on a few of these techniques and models. These models are unsuitable for remote field work as they require either extensive calculations on a mainframe computer or a highly subjective evaluation of the sound speed vertical profile. This report describes a relatively simple technique, the Blast Operational Overpressure Model (BOOM), for predicting airblast propagation at remote sites without the benefit of mainframe computers. No claims are made regarding the merits of this technique compared with others in use. The BOOM was developed for use in field operations at remote locations and it is capable of producing accurate results using a limited memory portable computer.

TABLE 1. BLAST PROPAGATION PREDICTION TECHNIQUES

| Model | Method | Computational requirements |
|---|---|---|
| 1. Sound Intensity Prediction System (SIPS) (Ref. 1) | Ray tracing to determine focal points. Capable of considering terrain. Empirical sound intensity predictions. | Mainframe computer |
| 2. Inverted FACT Model (Ref. 2) | Deterministic. Uses asymptotic approximation to prevent infinite intensities in the regions of caustics. | Mainframe computer |
| 3. A Prediction Method for Blast Focusing (Graphical) (Refs. 3,4 and and 5 describe similar methods) | Velocity of sound profiles are used with graphs to determine focal point location. Empirical overpressure equations. Subjective graphical analysis. | Sound Velocity profile and overpressure predictions can be calculated with pocket calculator. |
| 4. Focus: Computerized Aid for Making Sound Propagation Forecasts (Ref. 6) | Ray tracing. Computes focus location and overpressure amplification factor | Microcomputer |

## PREDICTION MODEL

Richard Lorenz (Ref. 7) developed an empirical overpressure prediction model for explosions of Mark-82, 500-lb bombs at Bloodsworth Island, Maryland. Overpressure measurements were made 25 km from the detonations of air-dropped Mark 82 bombs with airblast propagation over flat, marshy terrain and open water. Lorenz incorporated the refractive effects of the atmosphere into a single function, the Beta parameter. This parameter represents the atmospheric condition which has the greatest effect on airblast refraction; i.e., the maximum difference in the speed of sound between the surface and the altitude where A = arctangent ($\Delta V/\Delta Z$) is a maximum, as shown on Fig. 1.

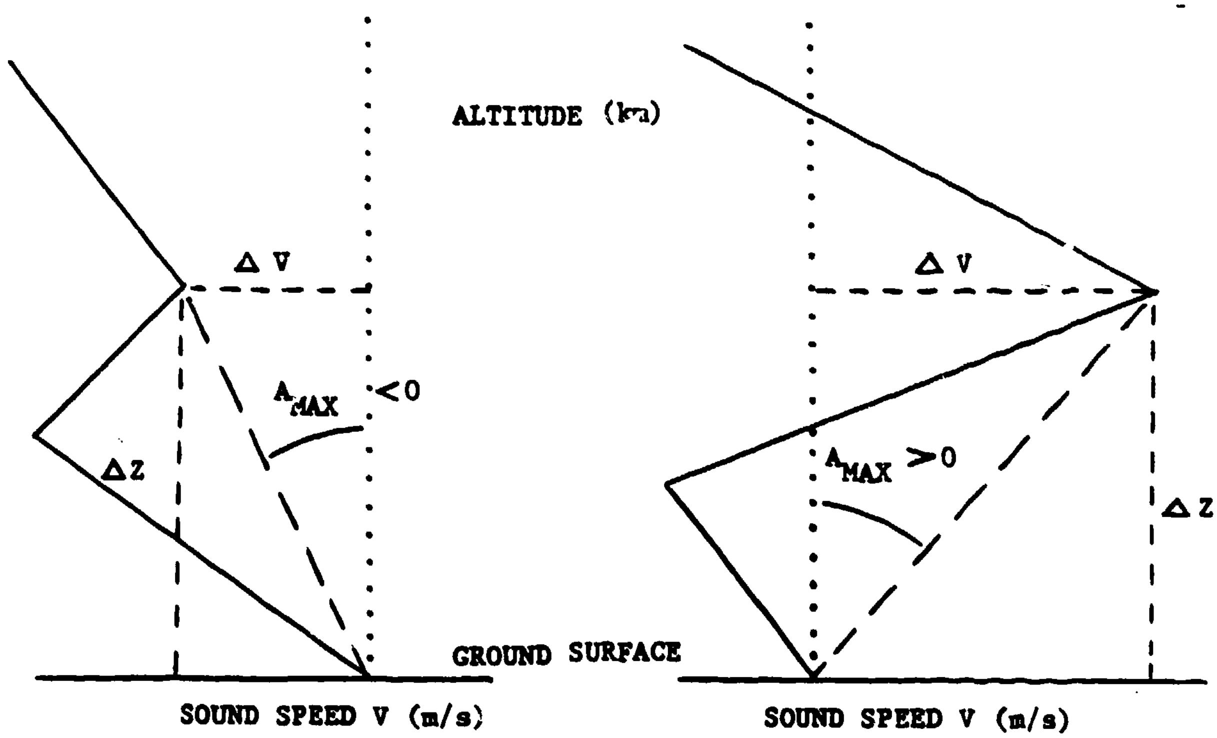



Figure 1. Sound speed profiles defining terms for the Beta parameter. (Left figure is an example of a negative Beta parameter. Right figure depicts a positive Beta parameter. Solid lines are the sound speed vertical profiles. Dotted line is the surface sound speed value for comparison with other levels. Small dashed lines are magnitudes of $\Delta V$ and $\Delta Z$. The angles designated $A_{max}$ are the maximum values of arctangent $\Delta V/\Delta Z$.)

The magnitude of the Beta parameter along a particular direction is computed from the maximum value of A given by the equation:

$$B = \text{arctangent } [3 * (\Delta V/\Delta Z) * (R/C)] \quad (2)$$

where

| | | |
|---|---|---|
| B = | Beta parameter for selected direction | (deg) |
| R = | Distance to location of interest | (km) |
| C = | Sound speed at the surface | (m/s) |
| ΔV = | Sound speed difference related to A in Fig. 1 | (m/s) |
| ΔZ = | Height of ΔV above ground level | (km) |

Lorenz' airblast measurements represent the positive overpressure amplitude of the airblast on the assumption that the measurements are sufficiently far-field that the peak positive and negative overpressures are approximately equal. The weather conditions affecting airblast propagation showed a significant variation in the vertical temperature gradient and wind velocity. Resultant Beta parameters ranged from a +81 (strong enhancement) to a -26 (moderate attenuation). A least squares fit to the data has the following equation:

$$L = 103.1 + B/5.3 \quad (3)$$

where

| | | |
|---|---|---|
| L = | Instantaneous peak overpressure | (dB) |
| B = | Beta parameter as previously defined | (deg) |

Equation 3 has a standard deviation of 7.6. Lorenz applied the results from previous detonations with yields ranging from 45 to 540,000 kg at distances from 5 to 50 km to develop the yield and range scaled predictive equation:

$$L = 103.1 + B/5.3 + 20*\text{LOG } [(S/1013)^{0.556}*(W/110)^{0.444}*(25/R)^{1.333}] \quad (4)$$

where:

| | | | |
|---|---|---|---|
| L | = | Maximum peak overpressure | (dB) |
| B | = | Weather parameter, as previously defined | (deg) |
| S | = | Surface atmospheric pressure | (mbar) |
| W | = | TNT equivalent explosive weight | (kg) |
| R | = | Distance from explosion | (km) |

Equation 4 represents the mean expected overpressure. The one standard deviation above the mean is obtained by adding 8 dB; one standard deviation below the mean is obtained by subtracting 10 dB. Lorenz' model was developed with measurements in units of decibels. Decibels are an arbitrary scale measure used in the mechanical measurement of sound. This arbitrary scale is a function of the ratio of the instantaneous overpressure to 20 micropascals which is considered the threshold of human hearing. This relationship between decibels and pascals can be seen in the equation:

$$L = 20 \log_{10} (P/P_o)$$

where:

| | | | |
|---|---|---|---|
| L | = | Maximum peak overpressure | (dB) |
| p | = | instantaneous overpressure | (Pa x $10^6$) |
| $P_o$ | = | 20 micropascals | |

So an instantaneous overpressure reading of 20 micropascals is equal to a maximum peak overpressure of zero when expressed in decibels. The current standard of airblast intensity is units of pascals, where the conversion factor to pascals is given by:

$$PK = 0.00002 * 10^{(L/20)} \quad \text{(Pa)} \qquad (5)$$

Lorenz stated that his model appeared to contain the core of a fairly general prediction method. However, he added that further study would be needed to determine the applicability of the model outside the range of data from which it was derived. The next two sections demonstrate how well the model performs, with slight modifications, for the varied AFWL high-explosive test programs.

CONVENTIONAL HIGH EXPLOSIVES BLAST AND SHOCK (CHEBS) SERIES

This section describes the application of Lorenz' model for the AFWL Conventional High Explosives Blast and Shock (CHEBS) test series. The purpose of CHEBS, conducted near the southern perimeter of Kirtland AFB, was to test the effects of conventional Mark-83 1000-lb bombs on protective shelters and to characterize close-in overpressures. AFWL/WE monitored these tests to insure that unacceptable airblast would not extend to the southern suburbs of Albuquerque, approximately 15 km from the test site.

For all CHEBS shots, the airblast intensity was measured at a location 5 km east-northeast of the test site. Additional measurements at 7 and 10 km were added as more airblast measuring equipment became available. Overpressures were digitally recorded on Validyne Differential Pressure Transducers, Model P305D. The transducer is of a diaphragm type and capable of measuring in a range from 2 to 862 Pa, with the manufacturer's specifications indicating an accuracy of ± 0.5 percent at full scale; i.e., ± 4.3 Pa. Reference 6 gives a complete description of the Validyne specifications and Fig. 2 shows an example of the recorded airblast waveform from the Validyne.

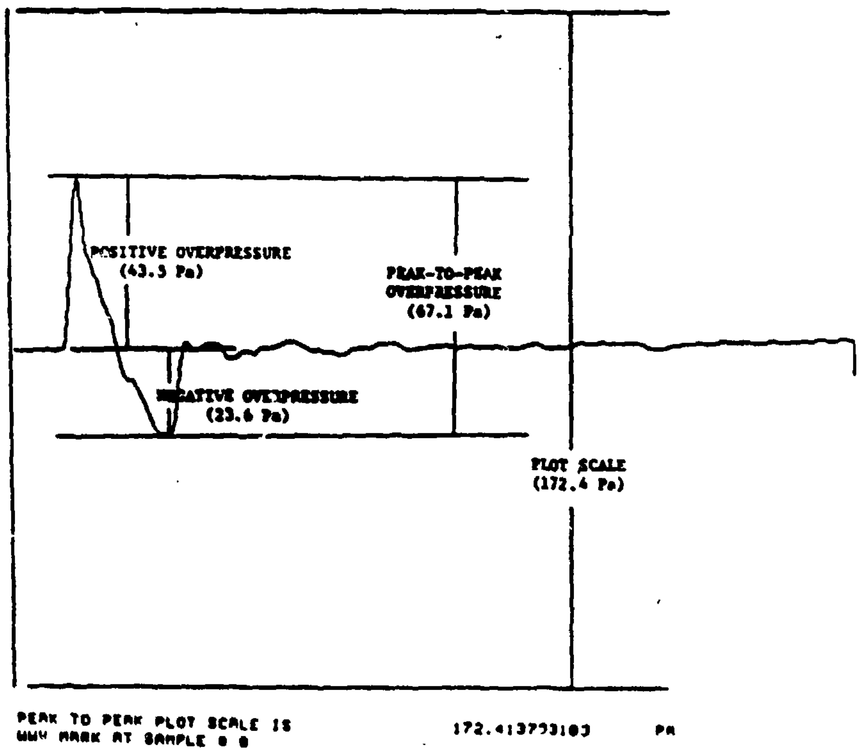



Figure 2. Example of Validyne plot of recorded airblast waveform.

Atmospheric conditions were determined using the regularly scheduled rawinsonde observations from the Albuquerque Airport, approximately 10 km west of the test site. Test-time vertical temperature profiles were estimated from the 1200 Greenwich Mean Time (GMT) rawinsonde data, adjusting for the observed surface temperature at shot-time, normal diurnal variations, and any significant advective changes. In addition, the winds aloft were measured at shot time by visually tracking a 10-g pilot balloon (pibal) with a theodolite. The pibal winds could not be determined above 5000 ft due to clouds or strong winds limiting the elevation angle toward the Manzano Mountains to the east. For winds above the limit of pibal data, measurements of the latest available Albuquerque rawinsonde winds were used with the necessary advective adjustments.

The Mark-83 bombs, which were placed either nose into the ground or on the side, effectively acted as a point surface detonation for far-field airblast intensity purposes. For a surface burst, the blast propagates hemispherically, rather than spherically as in the case of an elevated burst. Assuming the ground surface as a perfect reflector, the resulting overpressures are approximately equivalent to those from double the explosive yield. Thus, a charge weight of 550 kg TNT equivalent (2*275 kg) was used as the explosive source strength for the Mark-83 bombs.

The results of the CHEBS series are listed in Table 2. Weather conditions, listed in Appendix A, resulted in the Beta parameter ranging from -4 to +11. All overpressure measurements were well within the upper bound of Lorenz' prediction equation. However, the mean prediction tended to be low, especially when stronger winds aloft resulted in a positive Beta parameter.

TABLE 2. CHEBS RESULTS: MEAN AND MAXIMUM PREDICTIONS USING EQUATION 4

| Event | Measurement Location (Azimuth/Range) (deg/km) | Beta Parameter (deg) | Beta Height (ft) | Measured Overpressure (Pa) | Mean Prediction (Pa) | Maximum Prediction (Pa) |
|---|---|---|---|---|---|---|
| 7 | 070/5 | +9 | 2000 | 81 | 57 | 145 |
| 8 | 070/5 | +11 | 5000 | 99 | 60 | 151 |
| 9 | 070/5 | -4 | 1000 | 44 | 43 | 109 |
| 10 | 070/5 | -2 | 9000 | 44 | 45 | 114 |
| 12 | 070/5 | -3 | 7000 | 45 | 44 | 112 |
| 13 | 070/5 | 0 | 1000 | 71 | 47 | 119 |
| 13 | 070/10.4 | 0 | 1000 | 30 | 18 | 46 |
| 15 | 070/5 | +3 | 5000 | 85 | 50 | 132 |
| 15 | 070/10.4 | +8 | 5000 | 20 | 22 | 55 |
| 15 | 055/7.2 | +4 | 5000 | 30 | 37 | 82 |

Lorenz' mean prediction equation was adjusted to fit the data and given by the equation:

$$L = 106 + B/5.3 + 20*LOG[(P/1013)^{0.556}*(W/110)^{0.444}*(25/R)^{1.333}] \quad (6)$$

where

L = Peak overpressure (dB)
B = Weather parameter (deg)
P = Ambient pressure (mbar)
W = TNT equivalent explosive weight (kg)
R = Range of interest (km)

Equation 5 is used to convert the overpressure to Pascals. The maximum overpressure, consistent with Lorenz' upper bound, is obtained by adding 5 dB to the mean predictive value of Equation 6.

The predictions using the Equation 6 instead of Equation 4 are listed in Table 3. Figure 3 depicts the linear fit of the predicted overpressures to the observed values along with 95 percent confidence intervals (Ref. 9) for a future single response. The least squares fit to the data has the equation: Observed = -15.3012 + (1.2208 * predicted) with a correlation coefficient of 0.8801. The magnitude of the confidence intervals is wide but reflects the small sample size (10 measurements) rather than the goodness of fit. Since weather conditions were partially estimated from rawinsonde data nearly 6 h old, the predictions using Equation 6 in the CHEBS series were quite reasonable. The next section shows how the BOOM prediction technique performs much better when current weather data are available.

TABLE 3. CHEBS RESULTS: MEAN AND MAXIMUM PREDICTIONS USING EQUATION 6

| Event | Measurement Location (Azimuth/Range) (deg/km) | Beta Parameter (deg) | Beta Height (ft) | Measured Overpressure (Pa) | Mean Prediction (Pa) | Maximum Prediction (Pa) |
|---|---|---|---|---|---|---|
| 7 | 070/5 | +9 | 2000 | 81 | 79 | 145 |
| 8 | 070/5 | +11 | 5000 | 99 | 82 | 151 |
| 9 | 070/5 | -4 | 1000 | 44 | 59 | 109 |
| 10 | 070/5 | -2 | 9000 | 44 | 61 | 114 |
| 12 | 070/5 | -3 | 7000 | 45 | 63 | 112 |
| 13 | 070/5 | 0 | 1000 | 71 | 64 | 119 |
| 13 | 070/10.4 | 0 | 1000 | 30 | 24 | 46 |
| 15 | 070/5 | +3 | 5000 | 85 | 70 | 132 |
| 15 | 070/10.4 | +8 | 5000 | 20 | 29 | 55 |
| 15 | 070/7.2 | +4 | 5000 | 30 | 44 | 82 |

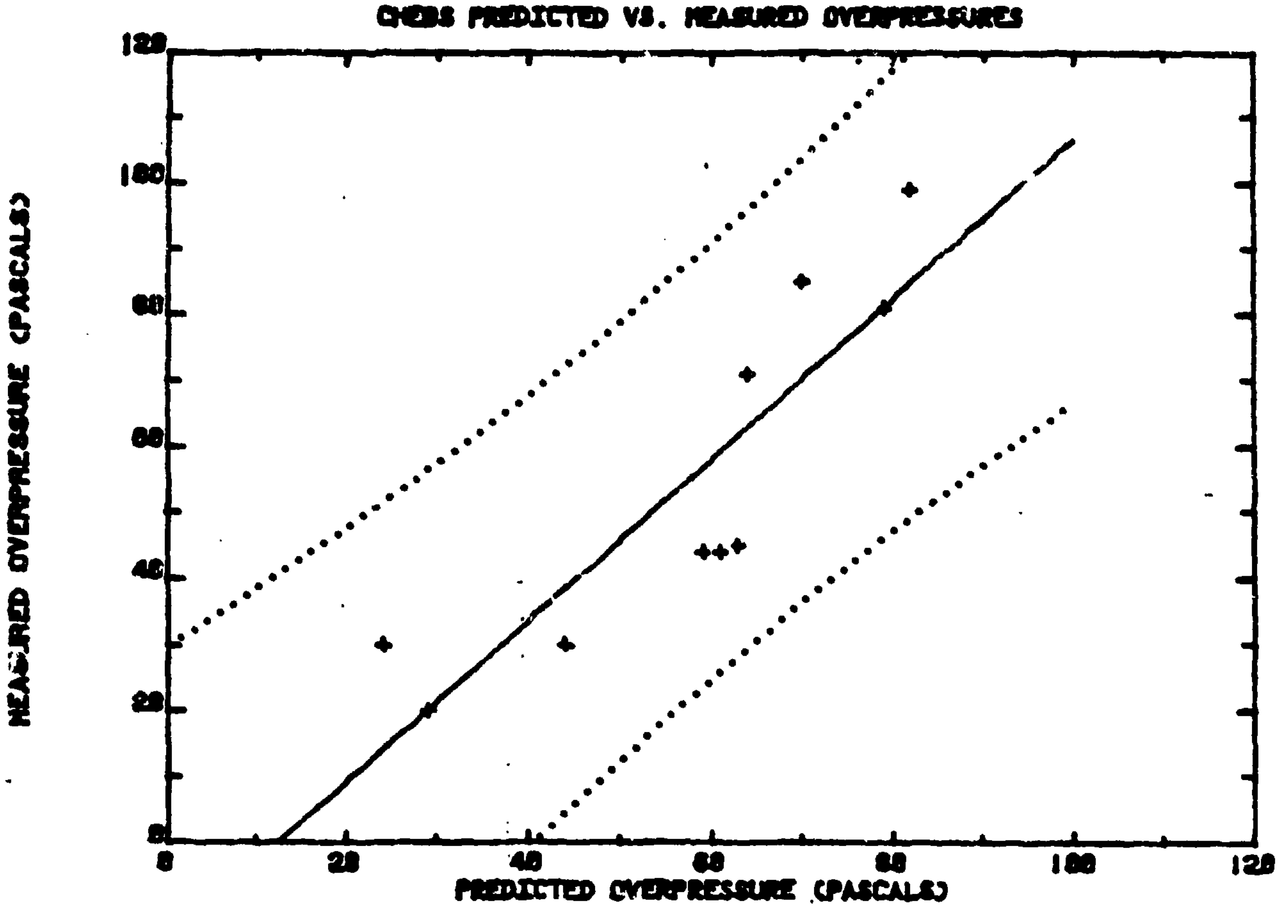



Figure 3. Correlation of predicted versus measured CHEBS overpressures. (The solid line is the linear least-squares fit: Measured = -15.3012 + [1.2208 * Predicted] with a correlation coefficient of 0.8801. Dotted lines are 95 percent confidence intervals for a future response.)

ICBM SILO SUPERHARDENING TECHNOLOGY (ISST) RESULTS

The purpose of the Intercontinental Ballistic Missile Silo Superhardening Technology (ISST) program, conducted at a remote site 45 km southeast of Yuma, Arizona, was to test the effects of simulated nuclear detonations on scale-sized missile silos. To attain the overpressures necessary to simulate a nuclear burst, the explosives (Iremite 60, TNT equivalent 0.90) were laid in a mostly circular form with an overburden of desert alluvial soil placed upon the explosives. The configuration was designed to confine most of the explosives effect to the test-bed area. However, for airblast prediction purposes, the design led to the problem of determining the portion of energy emitted to the atmosphere. This section describes the method of predicting the airblast attenuation caused by an overburden and presents the results of the BOOM model applied to airblast predictions for the ISST series.

Weather conditions (wind and temperature aloft) were gathered from rawinsonde data measured at the Yuma Proving Ground (YPG), 40 km northwest of the ISST site. Although some uncertainty was introduced into the weather data due to the distance from the test site, the YPG rawinsonde was the closest available data. The data were always recorded within 30 min of test time; therefore, uncertainty due to distance was minimized by the timeliness of the information. This problem was eliminated for the Large Size #1 (LS1) test (so far, the largest in the series) when the YPG weather team recorded the rawinsonde data at the ISST site. For the larger ISST tests, weather people from the Yuma Marine Corps Air Station took pibal wind observations at the site. Since temperature is a much more conservative meteorological quantity than wind velocity, the combination of the YPG upper air temperature data and the winds aloft observed at the site was the best compromise to adequately describe the state of the atmosphere for airblast propagation.

Airblast was again recorded on the AFWL Validynes for the ISST events. For the larger tests, additional measurements were made by Sandia National

Laboratory (SNL) people, who supported these tests with airblast predictions and measurements (Refs. 10, 11, and 12). Table 4 lists the test information, points of measurement, weather parameters, and the measured overpressures.

TABLE 4. ISST TEST RESULTS

| Example | Location (Azimuth/Range) (deg/km) | Beta Parameter (deg) | Measured Overpressure (Pa) |
|---|---|---|---|
| 1 | 355/17.1 | -15 | 24 |
| 2 | 355/3.6 | -7 | 133[a] |
| 3 | 360/13.8 | -26 | 11[a] |
| 4 | 341/3.8 | -14 | 345[a] |
| 5 | 359/19.3 | -53 | 28[a] |
| 6 | 340/14.4 | -21 | 14 |
| 7 | 355/16 | +4 | 40 |
| 8 | 355/3.3 | +1 | 414[a] |
| 9 | 337/11.3 | -10 | 21 |
| 10 | 340/9.6 | -16 | 20 |
| 11 | 337/5.3 | -5 | 96 |
| 12 | 337/15.6 | -46 | 32 |
| 13 | 330/9.7 | -14 | 37[a] |
| 14 | 340/3.5 | -7 | 80 |
| 15 | 330/16.2 | +10 | 58 |
| 16 | 340/2.5 | -1 | 196 |
| 17 | 330/11.3 | +7 | 38 |
| 18 | 340/14.4 | -36 | [illegible] |
| 19 | 300/2.1 | -2 | 373 |
| 20 | 360/14.2 | +3 | 28[a] |
| 21 | 336/9.6 | -33 | 82 |
| 22 | 360/18.6 | -34 | 7[a] |
| 23 | 330/11.3 | -16 | 36 |
| 24 | 336/9.7 | -33 | 75[a] |
| 25 | 340/9.6 | -14 | 28 |
| 26 | 355/14.5 | -28 | 14 |
| 27 | 330/9.7 | +6 | 62[a] |
| 28 | 340/3.5 | -5 | 114 |
| 29 | 340/14.4 | -24 | 8 |
| 30 | 340/14.4 | -1 | 6 |
| 31 | 355/13.9 | -44 | 39[a] |
| 32 | 338/5.9 | +4 | 190[a] |
| 33 | 360/13.8 | -44 | 49 |

[a] SNL measurement.

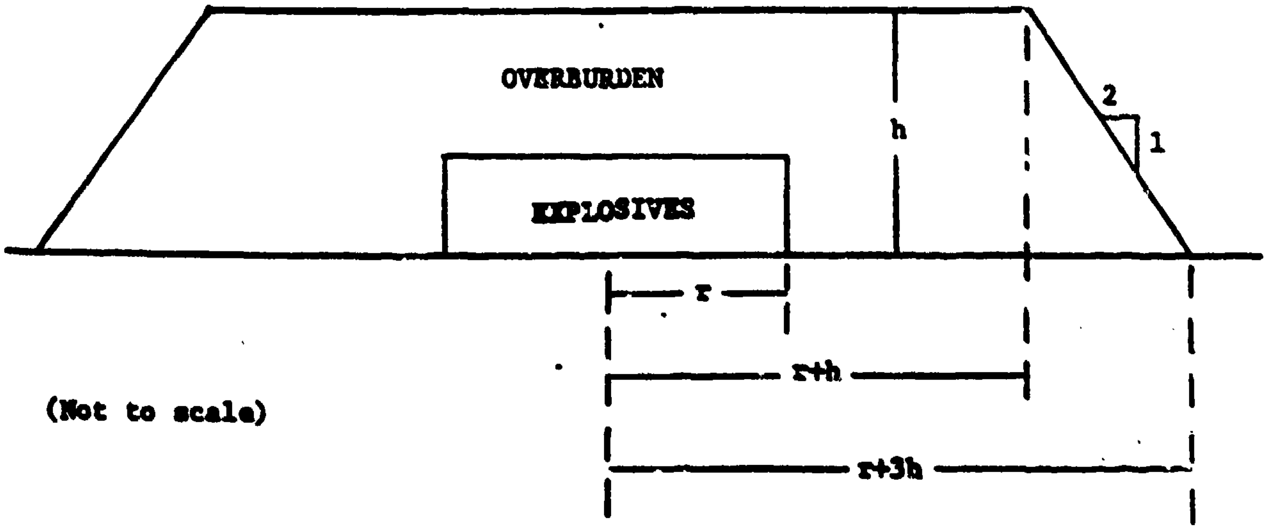
To determine the airblast attenuation effect of the ISST overburden configuration, the BOCM predictive equation (Equation 6) was solved for the amount of explosive weight required to produce the observed overpressure for the range of interest and the weather conditions. In effect, this procedure eliminates the overburden effect by treating the explosion as a point source surface detonation. Therefore, the percentage ratio of the "apparent weight" to the total explosive weight describes the portion of energy remaining as airblast after the explosive energy has been expanded to remove the overburden. The last column of Table 5 shows the percentage of the total explosive weight that resulted in the measured overpressure at each location. For the series, values ranged from less than 1 percent to nearly 11 percent.

J.W. Reed (Ref. 13) reasoned that the airblast emanating from beneath an overburden should depend on the amount of explosives, the area over which it is laid, the overburden mass, and the time to venting. However, he added that the time and character of the explosive venting, i.e., the failure of the overburden containment, should depend on the texture of the overburden material. Any physical assessment of that characteristic would be difficult. On the other hand, Reed observed that the fractional amount of energy expended in lifting the overburden to its venting point depends on the overburden mass per unit explosive area. Thus, the vented airblast should have some relationship to the overburden mass per unit explosive mass.

As previously discussed, the purpose of the ISST overburden was to induce large overpressures by confining most of the explosive energy to the test-bed area. As depicted in Fig. 4, the explosives were laid in a nearly circular area with the overburden built to a prescribed depth over the explosives. The depth of the explosives was negligible compared to the overburden height. The edge of the overburden extended beyond the explosives extremity to a distance equal to the overburden height and then extended to the ground on a 2:1 grade. This configuration was designed to attain an equal amount of overburden in all directions from the explosives.

TABLE 5. ISST APPARENT WEIGHT (% OF EXPLOSIVE WEIGHT)

| Example | Measurement Location (km) | Apparent Weight (% of Explosive Weight) |
|---|---|---|
| 1 | 17.1 | 10.915 |
| 2 | 3.6 | 2.707 |
| 3 | 13.8 | 1.849 |
| 4 | 3.8 | 2.220 |
| 5 | 19.3 | 6.497 |
| 6 | 14.4 | 4.999 |
| 7 | 16.0 | 6.438 |
| 8 | 3.3 | 6.347 |
| 9 | 11.3 | 1.824 |
| 10 | 9.6 | 4.477 |
| 11 | 5.3 | 4.511 |
| 12 | 15.6 | 3.627 |
| 13 | 9.7 | 4.187 |
| 14 | 3.5 | 3.163 |
| 15 | 16.2 | 10.955 |
| 16 | 2.5 | 4.734 |
| 17 | 11.3 | 1.299 |
| 18 | 14.4 | 3.012 |
| 19 | 2.1 | 5.140 |
| 20 | 14.2 | 4.707 |
| 21 | 9.6 | 3.544 |
| 22 | 18.6 | 2.633 |
| 23 | 11.3 | 6.866 |
| 24 | 9.7 | 3.140 |
| 25 | 9.6 | 5.006 |
| 26 | 14.5 | 3.112 |
| 27 | 9.7 | 2.357 |
| 28 | 3.5 | 3.681 |
| 29 | 14.4 | 2.841 |
| 30 | 14.4 | 0.583 |
| 31 | 13.9 | 3.458 |
| 32 | 5.9 | 6.285 |
| 33 | 13.8 | 5.388 |




(Not to scale)

Figure 4. Test-bed configuration for the ISST series. (Explosives and overburden are laid in a nearly circular form. The dimensions r, r + h, and r + 3h are radii. The depth of explosives is negligible compared to the overburden height.)

Many approaches were tried to empirically describe the airblast attenuation as a result of the overburden. The best relationship resulted when the ratio of the explosive weight and the total overburden mass was correlated with the mean apparent explosive weight for each individual test. The entire overburden mass was used to calculate the overburden factor with the assumption of a hemispherically radiating blast wave. This accounts for the portion of blast energy needed to move the intervening overburden in all directions before venting to the atmosphere. The overburden factor calculated for the ISST series is:

$$Z = W/(O*D) \tag{7}$$

where

| | | |
|---|---|---|
| Z = | Overburden factor | (kg explosive/kg overburden) |
| W = | TNT equivalent explosive weight | (kg) |
| O = | Overburden volume | ($m^3$) |
| D = | Density of overburden soil | ($kg/m^3$) |

The density of the alluvial soil was measured after each test and found to be 1845 $kg/m^3$, ± 5 percent. (Note: Equation 7 has been tested for only this density.)

The equation derived to account for the overburden effects has the form:

$$ZZ = -0.0146 + (11.5157*Z) \tag{8}$$

where

ZZ = Effective explosive weight factor

Z = Overburden factor from Equation 7

The correlation coefficient of the linear fit is 0.7660. Figure 5 graphically shows the least squares fit of the data. Scatter is evident in the data; however, the overburden factor Z does have a positive linear correlation with the apparent explosive weight. As an example, if an equal overburden configuration was used with an increased explosive weight, Equation 8 correctly predicts an increased apparent weight resulting in increased airblast effect. Conversely, an increased overburden volume with the same explosive weight would lead to a decreased airblast.

The overburden attenuation (Equation 8) was used in the BOOM prediction equation (Equation 6) to calculate the explosive weight for the ISST events. The prediction results are listed in Table 6. The 95 percent confidence limits (Ref. 9) were computed for a single future response. Based on the results of 33 overpressure measurements, the upper bound for predictions in the ISST series is:

$$PM = PK + 43.2838*[1.0303 + ((PK-88.1212)^2/389009.5152]^{1/2} \tag{9}$$

where

PM = Upper bound on the BOOM prediction (Pa)

PK = BOOM mean prediction (Pa)

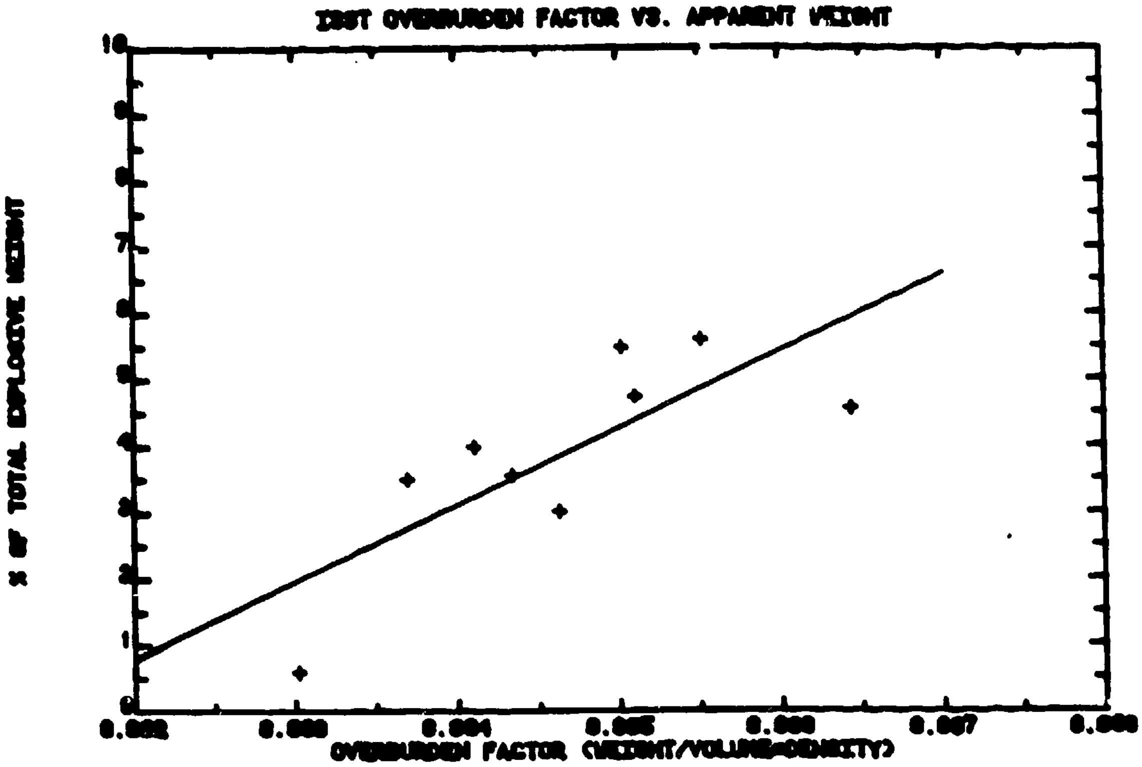


Figure 5. Correlation of the ISST overburden factors and the mean apparent explosive weights (percent of laid explosive weights). (The solid line is the linear least-squares fit: Percent of total explosive weight = 100 x ZZ, with a correlation coefficient of 0.7660.)

TABLE 6. ISST BOOM OVERPRESSURE PREDICTIONS

| Example | Measurement Distance (km) | Beta (deg) | Measured Overpressure (Pa) | Predicted Overpressure (Pa) |
|---|---|---|---|---|
| 1 | 17.1 | -15 | 24 | 17 |
| 2 | 3.6 | -7 | 133[a] | 152 |
| 3 | 13.8 | -26 | 11[a] | 17 |
| 4 | 3.8 | -14 | 345[a] | 444 |
| 5 | 19.3 | -53 | 28[a] | 22 |
| 6 | 14.4 | -21 | 14 | 15 |
| 7 | 16.0 | +4 | 40 | 48 |
| 8 | 3.3 | +2 | 414[a] | 372 |
| 9 | 11.3 | -10 | 21 | 33 |
| 10 | 9.6 | -16 | 20 | 17 |
| 11 | 5.3 | -5 | 96 | 99 |
| 12 | 15.6 | -46 | 32 | 33 |
| 13 | 9.7 | -14 | 37[a] | 35 |
| 14 | 3.5 | -7 | 80 | 79 |
| 15 | 16.2 | +10 | 58 | 55 |
| 16 | 2.5 | -1 | 196 | 190 |
| 17 | 11.3 | +7 | 38 | 82 |
| 18 | 14.4 | -36 | 7 | 8 |
| 19 | 2.1 | -2 | 373 | 363 |
| 20 | 14.2 | +3 | 28[a] | 56 |
| 21 | 9.6 | -33 | 82 | 86 |
| 22 | 18.6 | -34 | 7[a] | 9 |
| 23 | 11.3 | -16 | 36 | 27 |
| 24 | 9.7 | -35 | 75[a] | 78 |
| 25 | 9.6 | -14 | 28 | 25 |
| 26 | 14.5 | -28 | 14 | 15 |
| 27 | 9.7 | +6 | 62[a] | 99 |
| 28 | 3.5 | -5 | 114 | 138 |
| 29 | 14.4 | -24 | 8 | 8 |
| 30 | 14.4 | -1 | 6 | 11 |
| 31 | 13.9 | -43 | 39[a] | 42 |
| 32 | 5.9 | +4 | 190[a] | 183 |
| 33 | 13.8 | -43 | 49 | 42 |

[a] SNL measurements

As shown on Fig. 6, the BOOM prediction technique produced excellent results, i.e., a 0.9471 slope of the linear least-squares fit and a correlation coefficient of 0.9788. Accurate predictions were made over a wide range of both test parameters and atmospheric conditions. Overpressure predictions were accurate at distances from 2.1 to 18.6 km at overpressure levels ranging from 6 to 414 Pa. Additionally, weather conditions were quite variable. Vertical gradients of both temperature and wind velocity resulted in the Beta parameter varying from +10 to -53. However, the ISST overburden factor [explosive weight/(overburden volume * overburden density)] was only between 0.003 and 0.007. Further verification is needed for airblast predictions using overburden factors beyond the ISST limits.

A computer program to incorporate the BOOM technique was written in BASIC programming language for use on a Radio Shack PC-2 portable microcomputer. See Appendix B for details of the program.

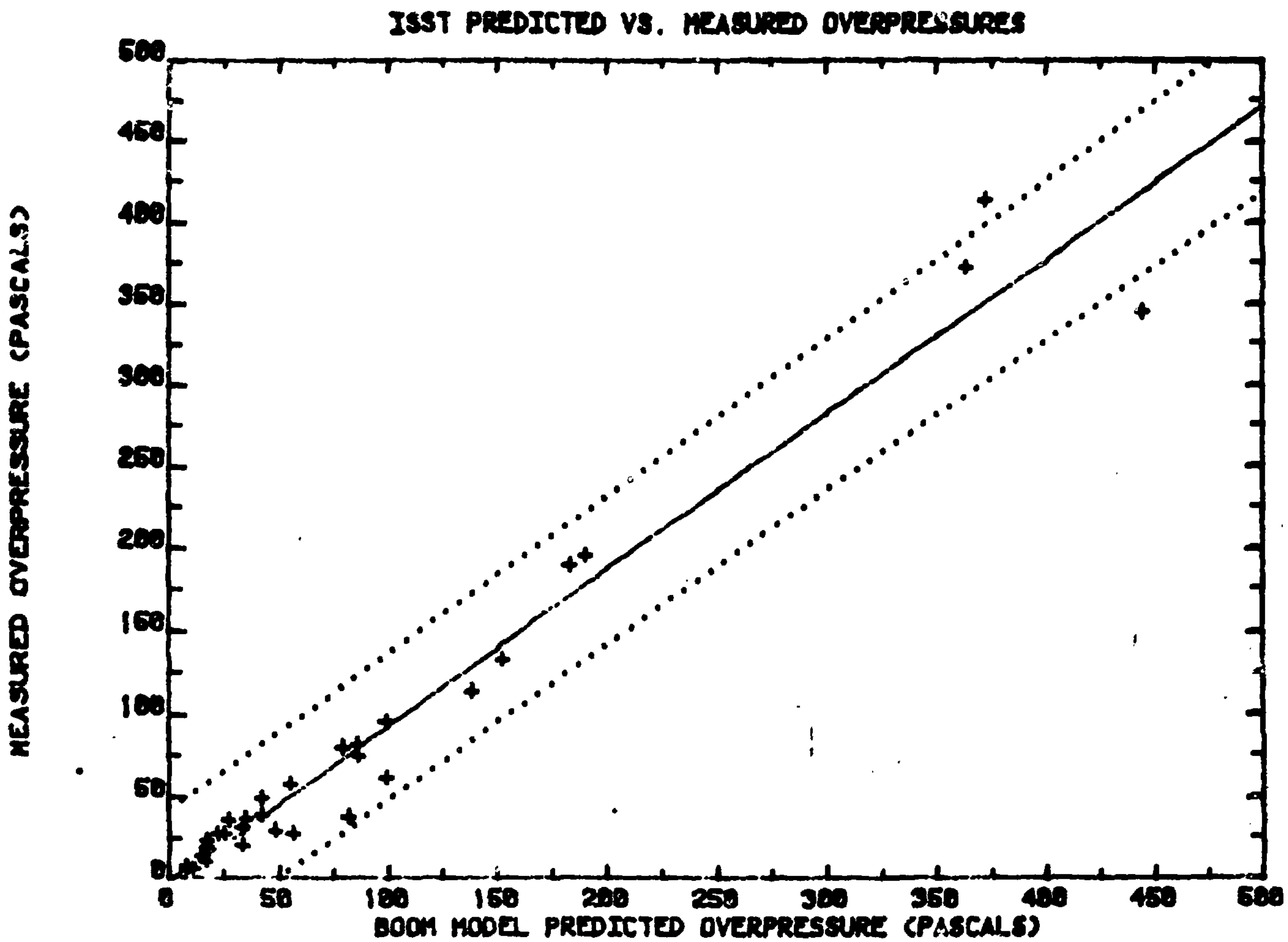



Figure 6. Correlation of predicted and measured ISST overpressures. (The solid line is the linear least-squares fit: Measured = -1.8014 + (0.9471 * Predicted) with a correlation coefficient of 0.9788. Dotted lines are 95 percent confidence intervals for a future response.)

## CONCLUSION

An airblast prediction technique, the BOOM, has been presented. The BOOM was implemented on a Radio Shack PC-2 portable microcomputer and is particularly applicable for airblast predictions at remote locations where access to a mainframe computer is not available. The BOOM is a modification of a technique developed by the Naval Surface Weapons Center for predicting airblast intensities from 500-lb bomb explosions. The refractive effect of the atmosphere is incorporated into a single function, as opposed to ray-tracing techniques, to determine whether airblast intensity will be amplified or diminished by the atmosphere. Results of airblast intensity measurements from 1000-lb bomb explosions demonstrate the validity of the original technique. An overburden factor, based upon the volume of soil placed upon the explosives, has been developed to predict the airblast emanating from beneath an alluvial soil overburden. Airblast predictions using the BOOM were validated with measurements from the ISST program. The overburden airblast attenuation factor may not be valid for ratios of explosive weight to overburden volume exceeding the range of the ISST series. However, the general technique should be useful in developing attenuation factors for explosions with overburdens.

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13. Reed, J.W., Recent Studies of Airblast from Buried Charges for Environmental Protection from HEST Events, Sandia National Laboratories, Division 7111, Albuquerque, New Mexico, June 1983.

# APPENDIX A

## WEATHER DATA AND SOUND SPEED PROFILES-CHEBS SERIES

This appendix lists the atmospheric conditions and the resultant tabular and graphical vertical sound speed profiles for the CHEBS high-explosive test series. The listings are copies of print-outs from the microcomputer used to run the program. For ease of readability of the sound speed plots, an enlarged copy of the first plot is presented. See Section 4 for the methods of obtaining the meteorological data and the assumptions considered.

CHEBS7 11APR84

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 17 | 260 | 20 |
| 1 | 14.3 | 250 | 25 |
| 2 | 11.7 | 240 | 31 |
| 3 | 9.1 | 250 | 27 |
| 4 | 6.6 | 270 | 28 |
| 5 | 4.4 | 290 | 31 |
| 6 | 2.2 | 280 | 32 |
| 7 | 0.7 | 270 | 35 |
| 8 | -0.7 | 270 | 46 |
| 9 | -3.7 | 270 | 49 |
| 10 | -6.7 | 270 | 53 |

DIRECTION 70

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 351.5 | |
| 1.0 | 352.5 | 1.0 |
| 2.0 | 353.7 | 2.2 |
| 3.0 | 350.4 | -1.0 |
| 4.0 | 348.6 | -2.8 |
| 5.0 | 346.0 | -5.4 |
| 6.0 | 346.6 | -4.8 |
| 7.0 | 348.3 | -3.1 |
| 8.0 | 352.6 | 1.1 |
| 9.0 | 352.2 | 0.7 |
| 10.0 | 352.3 | 0.8 |

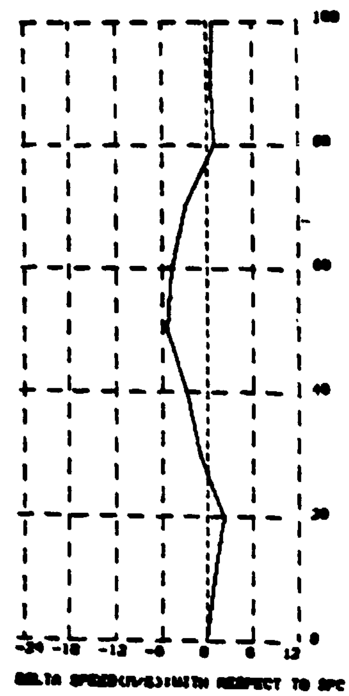


Figure A-1. CHEBS 7 weather data and sound speed profiles toward 070 deg.

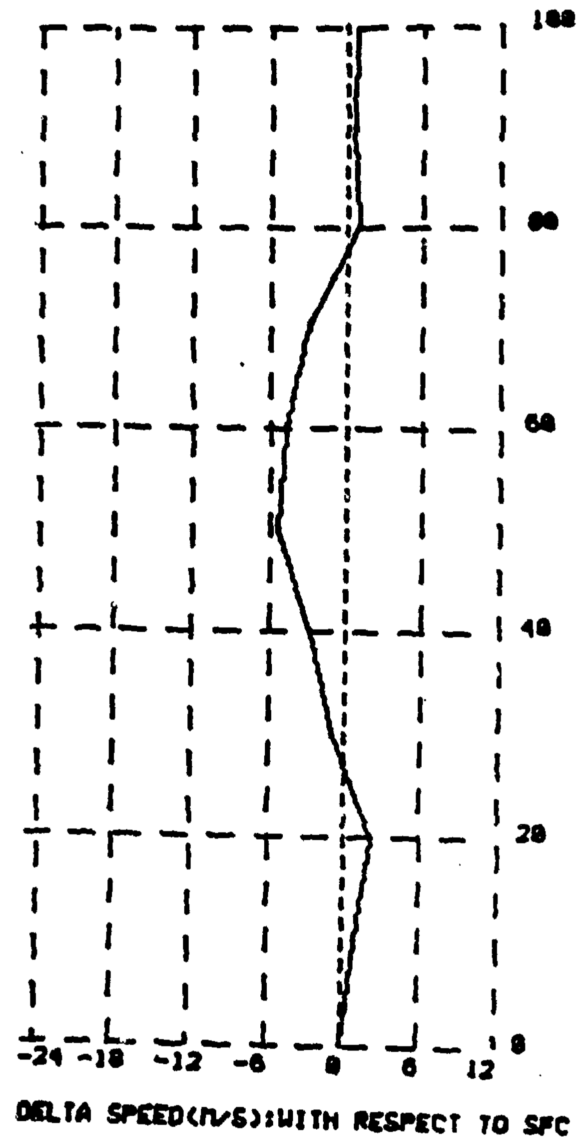



Figure A-2. Enlarged example of a sound speed plot.

DIRECTION 70

CHEBS8 3MAY84

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 15 | 270 | 10 |
| 1 | 12.6 | 270 | 10 |
| 2 | 10.2 | 275 | 16 |
| 3 | 10 | 281 | 13 |
| 4 | 10 | 280 | 25 |
| 5 | 9.3 | 280 | 35 |
| 6 | 5.6 | 290 | 35 |
| 7 | 1.9 | 295 | 39 |
| 8 | -1.6 | 295 | 40 |
| 9 | -5.1 | 300 | 41 |
| 10 | -6.4 | 295 | 43 |

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 345.1 | |
| 1.0 | 343.7 | -1.4 |
| 2.0 | 344.8 | -0.2 |
| 3.0 | 343.0 | -2.0 |
| 4.0 | 348.3 | 3.1 |
| 5.0 | 352.2 | 7.0 |
| 6.0 | 348.2 | 3.1 |
| 7.0 | 346.4 | 1.2 |
| 8.0 | 344.6 | -0.5 |
| 9.0 | 341.5 | -3.6 |
| 10.0 | 342.7 | -2.3 |

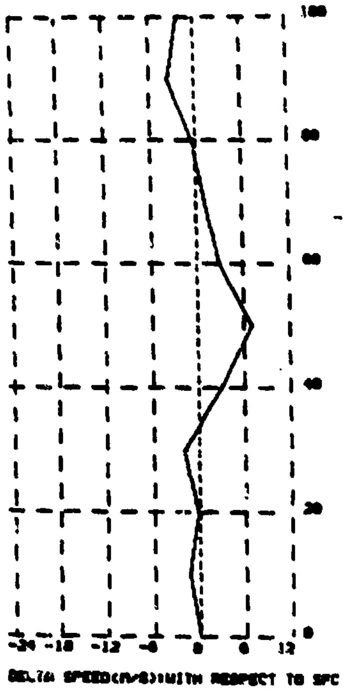


Figure A-3. CHEBS 8 weather data and sound speed profile toward 070 deg.

DIRECTION 70

CHEBS9 20AUG84

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 22 | 210 | 4 |
| 1 | 19.5 | 240 | 5 |
| 2 | 17.1 | 240 | 5 |
| 3 | 14.9 | 230 | 7 |
| 4 | 12.6 | 240 | 6 |
| 5 | 10.3 | 220 | 11 |
| 6 | 8.2 | 230 | 11 |
| 7 | 6.1 | 210 | 12 |
| 8 | 4 | 210 | 14 |
| 9 | 1.9 | 210 | 19 |
| 10 | -0.1 | 210 | 21 |

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 346.1 | |
| 1.0 | 345.5 | -0.5 |
| 2.0 | 344.1 | -1.9 |
| 3.0 | 343.7 | -2.4 |
| 4.0 | 342.0 | -4.1 |
| 5.0 | 342.4 | -3.6 |
| 6.0 | 341.6 | -4.5 |
| 7.0 | 339.7 | -6.3 |
| 8.0 | 339.2 | -6.8 |
| 9.0 | 339.9 | -6.1 |
| 10.0 | 339.4 | -6.6 |

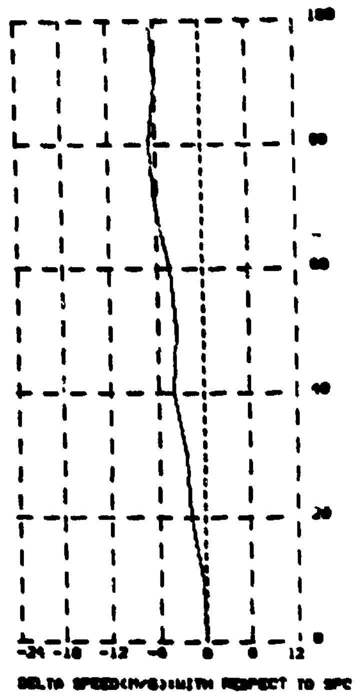



Figure A-4. CHEBS 9 weather data and sound speed profile toward 070 deg.

CHEBS10 27SEP84

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 12 | 330 | 5 |
| 1 | 10.7 | 330 | 4 |
| 2 | 9.4 | 340 | 4 |
| 3 | 8.1 | 335 | 9 |
| 4 | 7 | 325 | 11 |
| 5 | 4.2 | 320 | 11 |
| 6 | 1.7 | 310 | 12 |
| 7 | 0 | 305 | 12 |
| 8 | -1 | 305 | 13 |
| 9 | -1.9 | 285 | 15 |
| 10 | -3.5 | 285 | 15 |

DIRECTION 70

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 339.1 | |
| 1.0 | 338.2 | -0.8 |
| 2.0 | 337.1 | -1.9 |
| 3.0 | 336.7 | -2.3 |
| 4.0 | 337.1 | -1.9 |
| 5.0 | 335.9 | -3.2 |
| 6.0 | 335.5 | -3.6 |
| 7.0 | 334.9 | -4.1 |
| 8.0 | 334.6 | -4.5 |
| 9.0 | 336.4 | -2.6 |
| 10.0 | 335.5 | -3.6 |

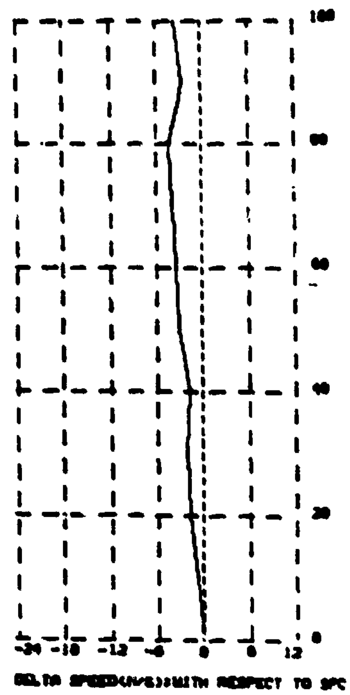


Figure A-5. CHEBS 10 weather data and sound speed profile toward 070 deg.

DIRECTION 70

CHEBS12 14FEB85

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 7 | 360 | 5 |
| 1 | 4.3 | 360 | 5 |
| 2 | 0.8 | 340 | 7 |
| 3 | -1.6 | 330 | 9 |
| 4 | -1.9 | 315 | 8 |
| 5 | -3.1 | 315 | 13 |
| 6 | -4.4 | 320 | 18 |
| 7 | -5.7 | 320 | 24 |
| 8 | -7.4 | 330 | 28 |
| 9 | -9.1 | 340 | 32 |
| 10 | -10.9 | 340 | 35 |

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 334.8 | |
| 1.0 | 333.2 | -1.6 |
| 2.0 | 331.9 | -2.8 |
| 3.0 | 331.3 | -3.5 |
| 4.0 | 332.0 | -2.8 |
| 5.0 | 332.3 | -2.5 |
| 6.0 | 331.8 | -2.9 |
| 7.0 | 332.1 | -2.7 |
| 8.0 | 329.4 | -5.4 |
| 9.0 | 325.9 | -8.9 |
| 10.0 | 324.8 | -10.0 |

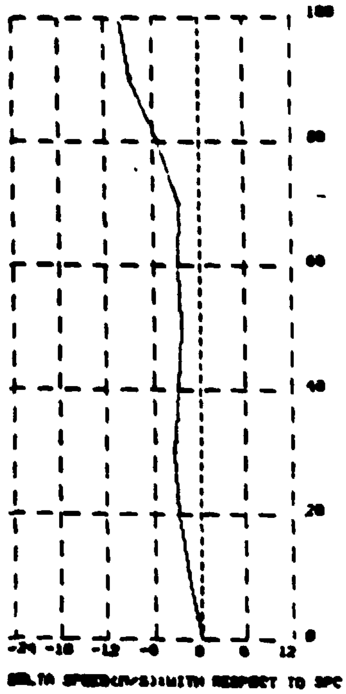



**Figure A-6.** CHEBS 12 weather data and sound speed profile toward 070 deg.

DIRECTION 70

CHEBS13 28FEB85

*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) |
|---|---|---|
| 0 | 11 | 190 5 |
| 1 | 8.7 | 210 6 |
| 2 | 5.9 | 230 6 |
| 3 | 3.1 | 280 10 |
| 4 | 0.8 | 300 15 |
| 5 | -1.3 | 300 13 |
| 6 | -3.4 | 280 10 |
| 7 | -5.5 | 270 10 |
| 8 | -7.7 | 260 10 |
| 9 | -9.9 | 250 12 |
| 10 | -11.9 | 240 15 |

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 339.3 | |
| 1.0 | 339.0 | -0.3 |
| 2.0 | 337.8 | -1.4 |
| 3.0 | 337.7 | -1.6 |
| 4.0 | 336.8 | -2.5 |
| 5.0 | 334.8 | -4.4 |
| 6.0 | 333.7 | -5.5 |
| 7.0 | 332.8 | -6.5 |
| 8.0 | 331.7 | -7.6 |
| 9.0 | 331.4 | -7.9 |
| 10.0 | 331.5 | -7.7 |

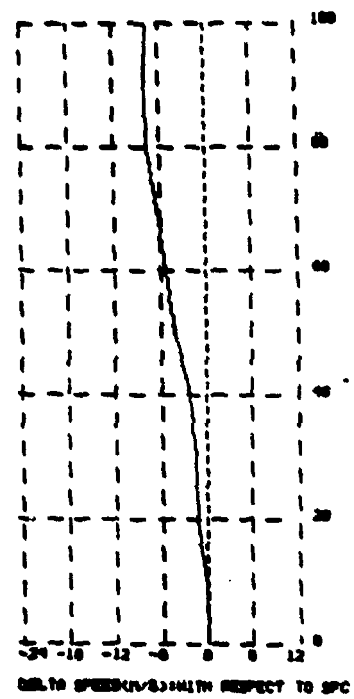


Figure A-7. CHEBS 13 weather data and sound speed profile toward 070 deg.

CHEBS15 25APR85

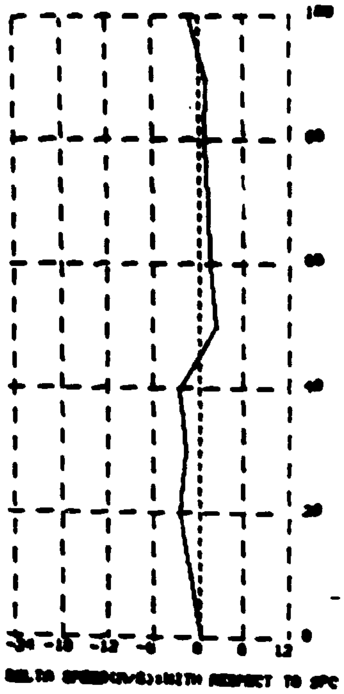
*WEATHER DATA*

| HGT (KFT) | TEMP (C) | WIND (KTS) | |
|---|---|---|---|
| 0 | 17 | 200 | 15 |
| 1 | 15.5 | 195 | 15 |
| 2 | 13 | 190 | 17 |
| 3 | 9.9 | 190 | 28 |
| 4 | 7.7 | 190 | 30 |
| 5 | 5.4 | 230 | 30 |
| 6 | 2.5 | 250 | 30 |
| 7 | -0.4 | 270 | 35 |
| 8 | -3.4 | 265 | 37 |
| 9 | -6.3 | 255 | 40 |
| 10 | -8.7 | 250 | 38 |

DIRECTION 70

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 346.4 | |
| 1.0 | 345.0 | -1.4 |
| 2.0 | 343.5 | -2.9 |
| 3.0 | 344.4 | -2.0 |
| 4.0 | 343.6 | -2.8 |
| 5.0 | 348.8 | 2.3 |
| 6.0 | 348.0 | 1.5 |
| 7.0 | 347.7 | 1.2 |
| 8.0 | 347.3 | 0.8 |
| 9.0 | 347.5 | 1.1 |
| 10.0 | 345.1 | -1.3 |



DIRECTION 55

*SOUND SPEED DATA*

| HGT (KFT) | SOUND SPEED (M/S) | DELTA SPEED (M/S) |
|---|---|---|
| 0.0 | 347.8 | |
| 1.0 | 346.5 | -1.2 |
| 2.0 | 345.3 | -2.4 |
| 3.0 | 347.3 | -0.4 |
| 4.0 | 346.7 | -1.0 |
| 5.0 | 349.7 | 1.9 |
| 6.0 | 347.5 | -0.2 |
| 7.0 | 345.5 | -2.2 |
| 8.0 | 345.4 | -2.3 |
| 9.0 | 346.4 | -1.3 |
| 10.0 | 344.5 | -3.2 |

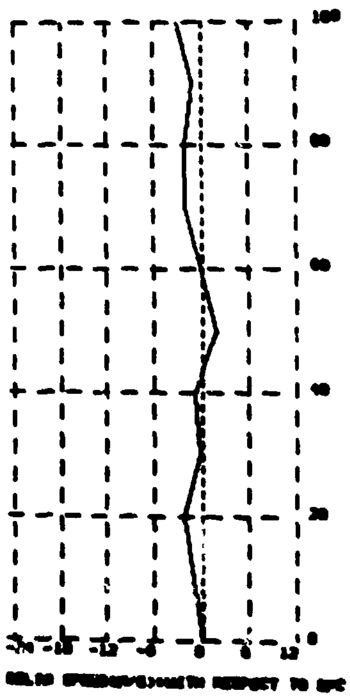


**Figure A-8. CHEBS 15 weather data and sound speed profiles toward 070 deg and 055 deg.**

# APPENDIX B

## DESCRIPTION OF THE BLAST OPERATIONAL OVERPRESSURE MODEL (BOOM)

This appendix describes the AFWL/WE BOOM used to predict far-field airblast intensity. The program is written in BASIC programming language for use on a Radio Shack TRS-80 PC-2 portable microcomputer. The BOOM program has many options. Airblast intensity is computed for either a standard surface detonation or a buried explosion. The model uses an attenuation factor to predict the airblast emitted from beneath an alluvial soil overburden. Weather information, to compute the vertical sound speed profile, may be input in the following ways: (1) rawinsonde pressure levels and temperatures, plus winds at standard 1000 ft intervals; (2) rawinsonde pressure levels and temperature, plus pilot balloon azimuth and elevation angles to compute pibal winds; and (3) temperature and wind at specified heights. The output statements and the sound speed plot subroutine are written for the PC-2 printer having only an 18 character field width. Therefore, users of the program will probably need to modify these statements for use on other machines. On the following pages are listings of the program variables and the BOOM program, and a description of the program flow.

## BOOM VARIABLE LISTING

AU,BU - trigonometric functions to compute the U component of the pibal wind

AV,BV - trigonometric functions to compute the V component of the pibal wind

AZ - azimuth of the pilot balloon at each timed measurement (deg)

B - maximum Beta parameter for a given direction and range (deg)

BH - altitude of maximum Beta parameter (kft)

CH - option to print vertical sound speed plot

DD - difference between direction of interest and wind direction at each height (deg)

DI - directions for airblast predictions (deg)

DN - number of directions for airblast predictions

DV - difference between surface sound speed and sound speed at each height (m/s)

DZ - geopotential thickness between each rawinsonde level, based on the hydrostatic approximation (ft)

EL - elevation of the pilot balloon at each timed observation (deg)

F - linear interpolation factor to compute temperature at the height of each wind data height

H - height of sound speed calculations, based upon input height of wind and temperature data (kft)

HD - height difference between successive rawinsonde pressure levels (ft)

II - counter for pibal wind calculations

IS - pibal observation interval (s)

IT - total time elapsed since pilot balloon release (s)

LA - previous pilot balloon azimuth ;used to compute pibal winds (deg)

LE - previous pilot balloon elevation ; used to compute pibal winds (deg)

LL - number of weather data levels

M - Beta parameter for each direction, range and height (deg)

MM - number of pilot balloon azimuth and elevation observations

NH - height of pilot balloon at each observation (ft)

NR - number of ranges for airblast prediction along each direction

P - rawinsonde pressure level (mbar)

PD - pibal wind direction (deg)

PH - previous height of pilot balloon; used to calculate pibal winds (ft)

PK - mean overpressure from BOOM (Pa)

PM - maximum overpressure from BOOM (Pa)

PS - pibal wind speed (kt)

R - ranges for airblast prediction along each direction (km)

RH - geopotential height of each rawinsonde pressure level (ft)

RL - number of rawinsonde pressure levels

RR - rise rate of pilot balloon depending on time since release (ft/s)

S - atmospheric surface pressure (mbar)

SZ - pilot balloon size (10 or 30 g)

T - temperature at each rawinsonde pressure level (°C)

TD - temperature difference between successive rawinsonde pressure levels (°C)

TE - option, surface or buried explosion

TK - rawinsonde temperature converted to Kelvin (K)

TN$ - heading, any desired entry

TP - option for wind input: rawinsonde or pibal

TT - temperature at the level of wind data; either actual or computed from rawinsonde data (°C)

TW - option for type of weather data input

U - east-west pibal wind component; used to compute pibal wind

V - north-south pibal wind component; used to compute pibal wind

VS - sound speed along the selected direction (m/s)

W - TNT equivalent apparent explosive weight (kg)

WD - wind direction at each height (deg)

WS - wind speed at each height (kt)

WT - TNT equivalent explosive weight (kg)

XH - height of layer averaged pibal wind (ft)

Z - overburden factor (kg explosives/kg soil overburden)

ZZ = effective explosive weight factor (resulting from overburden)

## BOOM COMPUTER PROGRAM LISTING

```
  1:"BOOM"
 10:DIM P(10),T(10
    ),TK(10),RH(10
    ),WD(21),WS(21
    )
 11:DIM TT(21),US(
    3,21),DU(3,21)
    ,DI(3),R(3,8),
    PK(3,8),NR(8)
 15:DIM B(3,8),PM(
    3,8),H(21),BH(
    3,8):WAIT 100
 30:INPUT "TEST LO
    CATION,DATE/TI
    ME";TN$
 32:INPUT "EXPLOSI
    VE WEIGHT(KG)"
    ;WT
 34:INPUT "SFC PRE
    SS(MB)";S
 36:INPUT "EXPLOSI
    ON? SFC-1,BURI
    ED-2";TE
 38:IF TE=1THEN
    LET W=2*WT:
    GOTO 49
 40:INPUT "OVERBUR
    DEN FACTOR ";Z
 42:ZZ=-.0146+(11.
    5157*Z):W=WT*Z
    Z
 49:INPUT "WANT PL
    OT? YES-1 NO-2
    ";CH
 50:INPUT "# OF DI
    R OF INT";DN
 60:FOR I=1TO DN
 70:INPUT "DIRECTI
    ON";DI(I)
 71:INPUT "# OF RA
    NGES ";NR(I)
 72:FOR J=1TO NR(I
    )
 73:INPUT "RANGE(K
    M) ";R(I,J)
 75:NEXT J:NEXT I
 90:PRINT "TYPE WE
    ATHER DATA?"
 92:INPUT "RAWIN-1
    ,HGT,TEMP,WND-
    2";TW
 94:IF TW=2THEN
    GOTO 1170
100:INPUT "# OF RA
    WIN LEVELS ";R
    L
120:FOR I=1TO RL
130:INPUT "PRESSUR
    E(MB) ";P(I)
140:INPUT "TEMP(C)
    ";T(I)
150:TK(I)=T(I)+273
    .2
160:NEXT I
220:PRINT "WIND DA
    TA NEEDED"
230:INPUT "WND DAT
    A? RAWIN-1;PIB
    AL-2";TP
240:IF TP=1THEN
    GOTO 900
250:INPUT "BALLON
    SIZE(GM) ";SZ
260:INPUT "OBS TIM
    E INTERVAL ";I
    S
270:INPUT "# PIBAL
    OBS ";MM
280:IT=0:PH=0:LA=0
    :LE=.01745:C1=
    0.33:C2=7.62:C
    3=7:RAD=π/180:
    II=0
290:IF SZ=10THEN
    GOTO 310
300:C1=C1*2:C2=C2*
    2:C3=C3*2
310:LPRINT "   PIB
    AL DATA"
315:LF 1:LPRINT "H
    GT(FT)    WIND(
    KT)"
340:LF 2
```

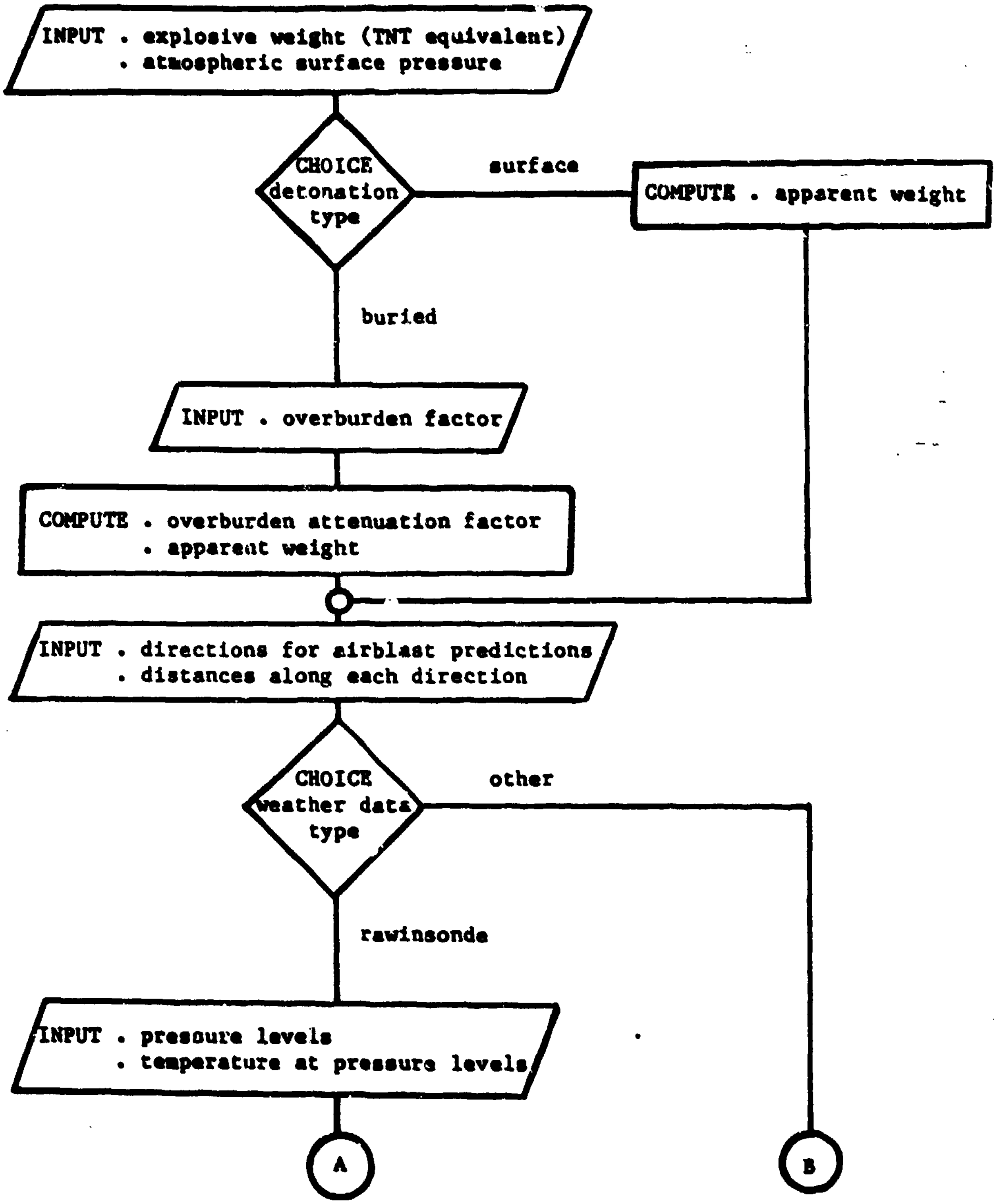
```
350:IT=IT+IS:RR=C2
    :II=II+1
360:IF IT<=75THEN
    LET RR=C1
370:IF IT>240THEN
    LET RR=C3
380:NH=PH+RR*IS:XH
    =(NH+PH)/2
390:INPUT "AZIMUTH
     ANGLE ;AZ
400:INPUT "ELEVATI
    ON ANGLE ";EL
402:AZ=AZ*RAD:EL=E
    L*RAD:RADIAN
410:AU=(NH*SIN AZ)
    /TAN EL:BU=(PH
    *SIN LA)/TAN L
    E:U=(AU-BU)/IS
420:AV=(NH*COS AZ)
    /TAN EL:BV=(PH
    *COS LA)/TAN L
    E:V=(AV-BV)/IS
430:PS=(SQR (U^2+V
    ^2))/3.2808
440:IF V<=0THEN
    GOTO 460
450:PD=ATN (U/V)/R
    AD+180:GOTO 47
    0
460:PD=ATN (U/V)/R
    AD
470:IF PD<=0THEN
    LET PD=PD+360
480:LA=AZ:LE=EL:PH
    =NH
490:LPRINT USING "
    ######";XH;
500:TAB 8:LPRINT
    USING "####";P
    D;:TAB 13:
    LPRINT USING "
    ###";PS*2
510:IF II<MMTHEN
    GOTO 350
520:LF 4
900:INPUT "# OF WN
    D LEVELS ";LL
910:FOR I=1TO LL
920:INPUT "HEIGHT(
    KFT) ";H(I)
930:INPUT "WND DIR
     ";WD(I)
940:INPUT "WND SPD
    (KT) ";WS(I)
950:WS(I)=WS(I)*.5
960:NEXT I
1000:RH(1)=0
1010:FOR I=2TO RL
1030:DZ=-48.0373*
     (TK(I)+TK(I-
     1))*LN (P(I)
     /P(I-1))
1040:RH(I)=RH(I-1
     )+DZ
1050:NEXT I
1060:C=0:NN=RL-1
1080:FOR I=1TO NN
1090:HD=RH(I+1)-R
     H(I):TD=T(I+
     1)-T(I)
1110:FOR J=1TO LL
1120:IF (H(J)*100
     0)<RH(I)THEN
     GOTO 1161
1130:IF (H(J)*100
     0)>RH(I+1)
     THEN GOTO 11
     62
1140:F=(H(J)*1000
     -RH(I))/HD:C
     =C+1:TT(C)=T
     D*F+T(I)
1161:NEXT J
1162:NEXT I
1165:GOTO 1200
1170:PRINT "ENTER
      HT, TEMP, WIN
     D"
1172:INPUT "HOW M
     ANY LEVELS?"
     ;LL
1174:FOR I=1TO LL
```

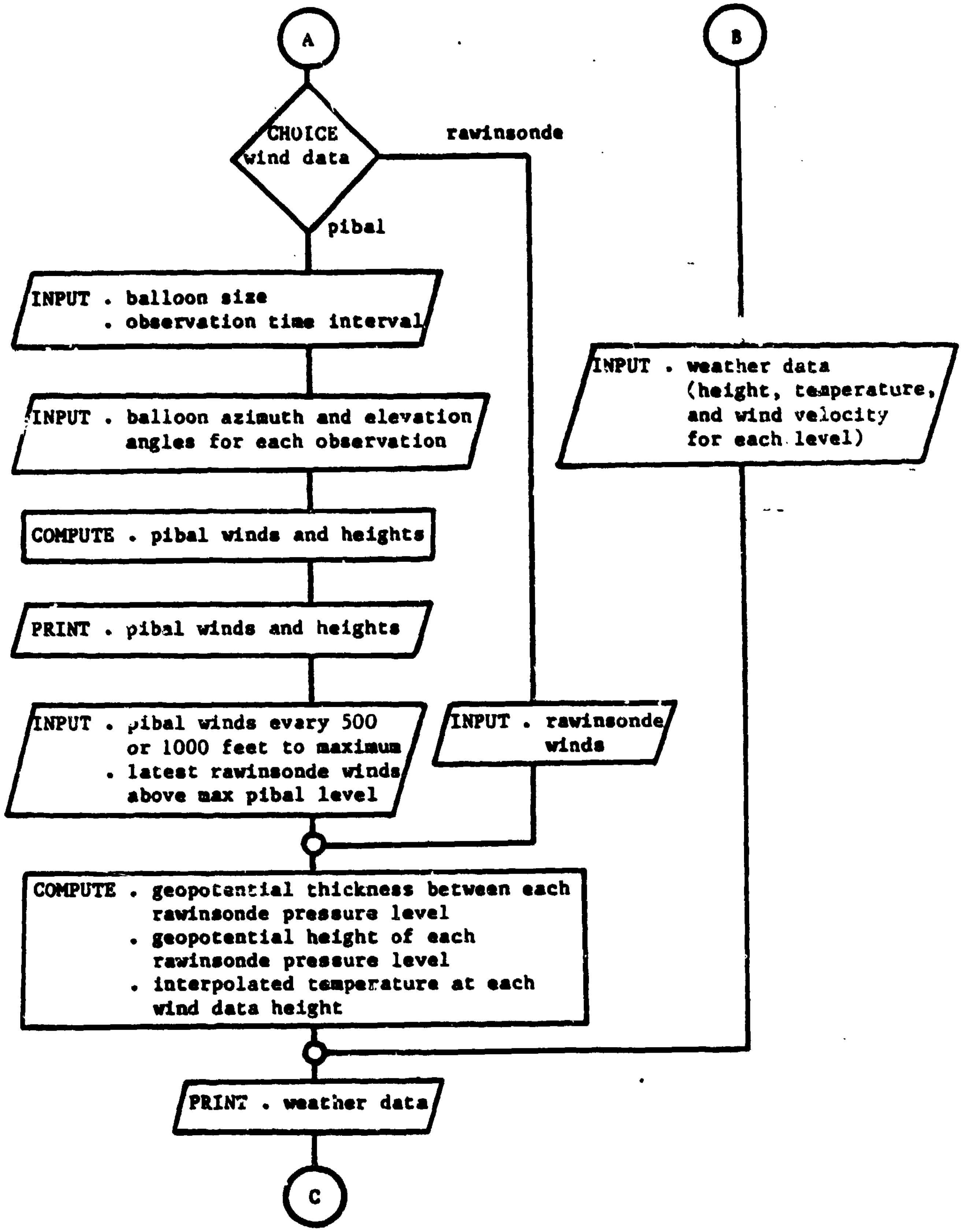
```
1176:INPUT "ENTER
      HEIGHT(KFT)
      ";H(I)
1178:INPUT "ENTER
      TEMP(C) ";T
     T(I)
1180:INPUT "ENTER
      WND DIR ";W
     D(I)
1182:INPUT "ENTER
      WND SPD(KT)
      ";WS(I)
1184:WS(I)=WS(I)*
     .5
1186:NEXT I
1200:FOR K=1TO DN
1210:DEGREE
1250:FOR M=1TO LL
1260:DD=DI(K)-WD(
     M)
1270:US(K,M)=331.
     5*SQR (1+TT(
     M)/273.2)-WS
     (M)*COS (DD)
1280:DU(K,M)=US(K
     ,M)-US(K,1)
1290:NEXT M
1300:NEXT K
1310:LPRINT TN$
1315:LF 1
1316:LPRINT "  *W
     EATHER DATA*
     "
1317:LF 1
1320:LPRINT " HGT
        TEMP  WIN
     D"
1322:LPRINT "(KFT
     )  (C)  (KTS
     )"
1325:LPRINT "----
     ------------
     --"
1330:LF 1
1340:FOR N=1TO LL
1360:LPRINT USING
     "###.#";H(N)
     ;
1361:TAB 6:LPRINT
     USING "###.#
     ";TT(N);
1362:TAB 11:
     LPRINT USING
     "####";WD(N)
     ;
1363:TAB 15:
     LPRINT USING
     "###";WS(N)*
     2
1380:NEXT N
1391:LF 2
1400:FOR K=1TO DN
1420:LPRINT "DIRE
     CTION ";
1425:LPRINT USING
     "####";DI(K)
1430:LF 1
1434:LPRINT "*SOU
     ND SPEED DAT
     A*"
1435:LF 1
1440:LPRINT " HGT
        SOUND  DEL
     TA"
1441:LPRINT "
        SPEED  SPE
     ED"
1442:LPRINT "(KFT
     ) (M/S)  (M/
     S)"
1443:LPRINT "----
     ------------
     --"
1500:FOR I=1TO LL
1510:LPRINT USING
     "###.#";H(I)
     ;
1530:TAB 6:LPRINT
     USING "####.
     #";US(K,I);
```

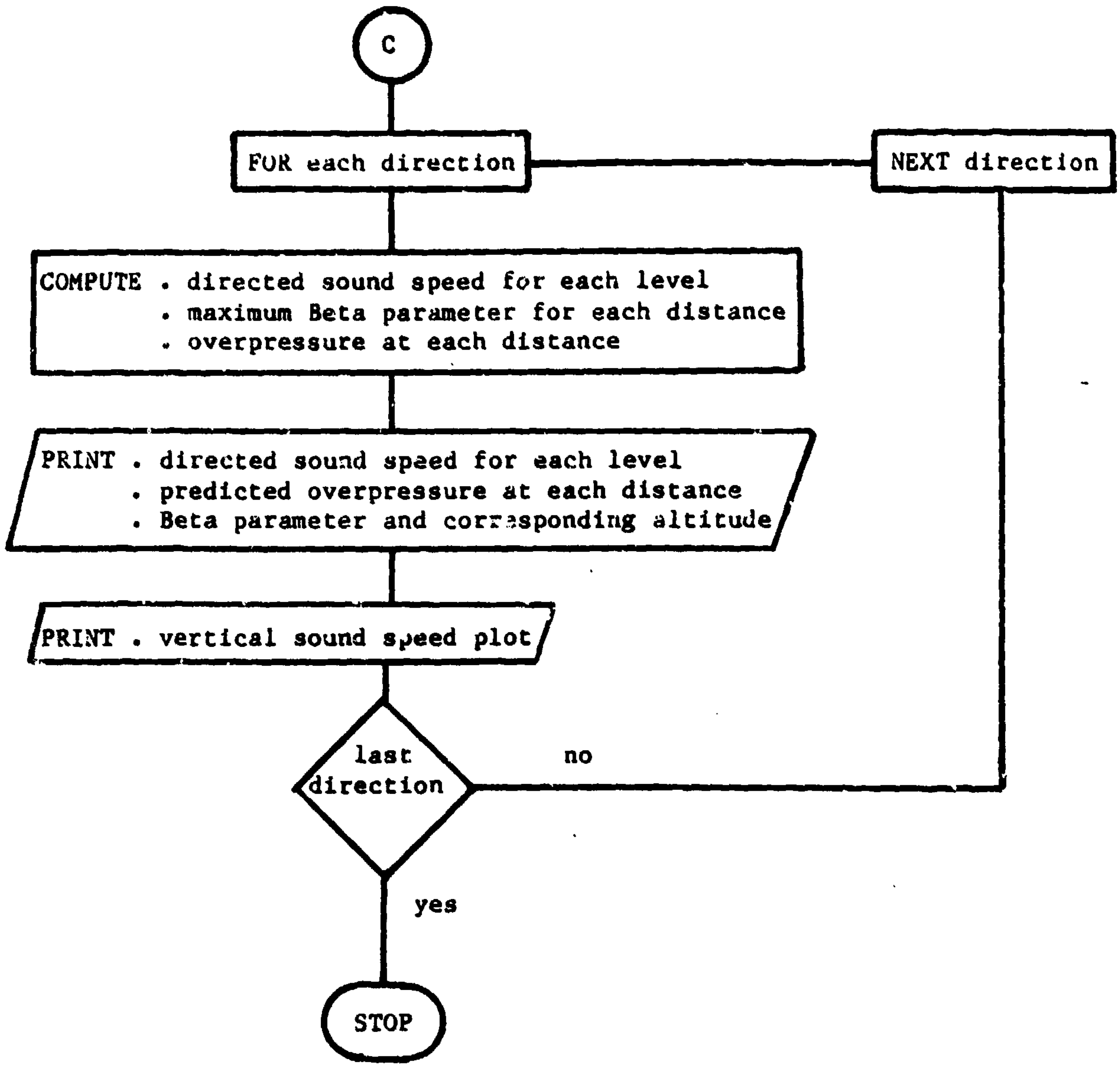
```
1550:TAB 13:
     LPRINT USING
     "###.#";DU(K
     ,I)
1560:NEXT I
1930:FOR I=1TO NR
     (K)
1938:BH(K,I)=0:B(
     K,I)=-1000
1939:B(K,I)=-1000
1950:FOR J=2TO LL
1960:DEGREE
1970:M=ATN (((3*R
     (K,I)*DU(K,J
     ))/(US(K,I)*
     H(J)*.3048))
     )
1979:IF M>B(K,I)
     THEN LET BH(
     K,I)=H(J)
1980:IF M>B(K,I)
     THEN LET B(K
     ,I)=M
1990:NEXT J
2000:L1=106+B(K,I
     )/5.3+20*LOG
     (((S/1013)^.
     556)*((W/110
     )^.444)*((25
     /R(K,I))^1.3
     33))
2005:PK(K,I)=.000
     02*10^(L1/20
     )
2008:IF TE=2THEN
     GOTO 2030
2010:L2=111+B(K,I
     )/5.3+20*LOG
     (((S/1013)^.
     556)*((W/110
     )^.444)*((25
     /R(K,I))^1.3
     33))
2015:PM(K,I)=.000
     02*10^(L2/20
     )
2020:GOTO 2040
2030:PM(K,I)=PK(K
     ,I)+43.2838*
     SQR (1.0303+
     (((PK(k,I)-8
     8.1212)^2)/3
     89009.5152))
2040:NEXT I
2060:LF 3
2062:LPRINT "  **
     PREDICTIONS*
     *":LF 1
2070:LPRINT "RANG
     E   OVER-PRE
     SS"
2072:LPRINT "(KM)
           (PA)"
2073:LPRINT "----
     ------------
     --":LF 1
2080:FOR I=1TO NR
     (K)
2090:TAB 1:LPRINT
     USING "###.#
     ";R(K,I);
2110:TAB 9:LPRINT
     USING "#####
     #.#";PK(K,I)
2115:TAB 6:LPRINT
     "MAX";
2116:TAB 9:LPRINT
     USING "#####
     #.#";PM(K,I)
2120:LF 1
2122:LPRINT "MAX
     BETA  ";B(K,
     I)
2123:LPRINT "HGT(
     KFT) ";BH(K,
     I)
2124:LF 2
2125:NEXT I
2126:IF CH=1THEN
     GOSUB 3000
2127:TEXT :LF 3
2130:NEXT K
2140:END
```

```
3000:REM  PLOT RO
     UTINE
3010:LF 3
3020:LPRINT "*SOU
     ND SPEED PLO
     T*"
3030:LPRINT " DIR
     ECTION";DI(K
     )
3040:TEXT :LF 23
3080:CSIZE 1:
     LPRINT "-24
     -18  -12   -
     6    0    6
       12"
3090:LF 1:CSIZE 1
4010:LPRINT "DELT
     A SPEED(M/S)
     :WITH RESPEC
     T TO SFC":LF
     -4:GRAPH
4040:LINE (0,0)-(
     180,0),8:
     CSIZE 1:
     LPRINT "  0"
4050:LINE (0,80)-
     (180,80),8:
     LPRINT "  4"
4060:LINE (0,160)
     -(180,160),8
     :LPRINT "  8
     "
4070:LINE (0,240)
     -(180,240),8
     :LPRINT " 12
     "
4080:LINE (0,320)
     -(180,320),8
     :LPRINT " 16
     "
4090:LINE (0,400)
     -(180,400),8
     :LPRINT " [illegible]
     "
4100:LINE (180,40
     0)-(180,0),8
     :LINE (150,0
     )-(150,400),
     8
4110:LINE (120,40
     0)-(120,0),3
     :LINE (90,0)
     -(90,400),8
4120:LINE (60,400
     )-(60,0),8:
     LINE (30,0)-
     (30,400),8
4130:LINE (0,400)
     -(0,0),9
4150:FOR I=1TO LL
     :H(I)=H(I)*2
     0:DU(K,I)=DU
     (K,I)*5:NEXT
     I
4160:GLCURSOR (12
     0,0):SORGN :
     FOR J=2TO LL
4170:LINE (DU(K,J
     -1),H(J-1))-
     (DU(K,J),H(J
     )),0
4180:NEXT J
4185:GLCURSOR (90
     ,150):ROTATE
     3:LPRINT "AL
     TITUDE (KFT)
     "
4190:FOR I=1TO LL
     :H(I)=H(I)/2
     0:DU(K,I)=DU
     (K,I)/5:NEXT
     I
4195:TEXT :CSIZE
     2:LF 20
5000:RETURN
```

BOOM COMPUTER PROGRAM FLOW CHART




A
B
CHOICE wind data
rawinsonde
pibal
INPUT . balloon size
. observation time interval
INPUT . balloon azimuth and elevation angles for each observation
COMPUTE . pibal winds and heights
PRINT . pibal winds and heights
INPUT . pibal winds every 500 or 1000 feet to maximum
. latest rawinsonde winds above max pibal level
INPUT . rawinsonde winds
INPUT . weather data (height, temperature, and wind velocity for each level)
COMPUTE . geopotential thickness between each rawinsonde pressure level
. geopotential height of each rawinsonde pressure level
. interpolated temperature at each wind data height
PRINT . weather data
C


C
FOR each direction
NEXT direction
COMPUTE . directed sound speed for each level
. maximum Beta parameter for each distance
. overpressure at each distance
PRINT . directed sound speed for each level
. predicted overpressure at each distance
. Beta parameter and corresponding altitude
PRINT . vertical sound speed plot
last direction
no
yes
STOP